

A MASSIVE DISK GALAXY AT $Z = 1.34$ ^{1,2}PIETER G. VAN DOKKUM³

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ABSTRACT

We report the discovery of a rapidly rotating disk in a K -selected galaxy at $z = 1.34$. Spatially resolved kinematics are determined from deep, moderate resolution Keck spectroscopy covering the redshifted [O II] 3727 Å line. A conservative estimate of the maximum rotation velocity $V_{\max} = 290 \pm 20 \text{ km s}^{-1}$, placing the galaxy among the most rapid rotators known. A *Hubble Space Telescope* WFPC2 image taken in the I_{F814W} filter (rest-frame U) shows that the [O II] emission originates in a ring of star forming regions $\sim 3''$ ($\sim 20 h_{75}^{-1} \text{ kpc}$) across. In the K -band the galaxy is compact, and its position coincides with the center of the star forming ring seen in the rest-frame near-UV. The galaxy has $M_V = -22.4 \pm 0.2$ ($\sim 3L_*$) in the rest-frame, and its spectral energy distribution is very well fitted by that of a redshifted Sb/c galaxy. The observed kinematics, morphology and spectral energy distribution are consistent with a massive bulge-disk system at $z = 1.34$. The lower limit on V_{\max} gives an upper limit on the offset from the present-day Tully-Fisher relation. The galaxy is overluminous by less than 0.7 ± 0.4 magnitudes in rest-frame V , consistent with previous studies of disk galaxies at lower redshift. Taken together, these results suggest that some of the most luminous spiral galaxies in the nearby Universe were already in place $\sim 10^{10}$ yr ago, placing a constraint on models for their formation.

Subject headings: galaxies: formation — galaxies: evolution — galaxies: structure of — galaxies: kinematics and dynamics — galaxies: spiral

1. INTRODUCTION

Hierarchical galaxy formation models predict that present-day massive disks were formed at $z \lesssim 1$ (Mo, Mao, & White 1998). The observational evidence concerning the existence of large, massive disks at high redshift is currently inconclusive. Studies of quasar absorption lines have demonstrated that structures with velocity widths up to $\sim 200 \text{ km s}^{-1}$ exist out to $z \sim 4$ (e.g., Prochaska & Wolfe 1997), but these may result from the motions of distinct kinematic systems within a common halo (e.g., Maller et al. 1999, Wolfe & Prochaska 2000). Another complication in kinematic studies of star forming galaxies at $z > 2$ is the effect of outflows on the observed line widths (Franx et al. 1997; Pettini et al. 2001).

Parallel to these studies there has been significant progress in the study of “normal”, morphologically identified disk galaxies at intermediate redshift. Studies of the structure of distant field galaxies with the *Hubble Space Telescope* (HST) indicate that the sizes of disks do not show strong evolution to $z \sim 1$, but that their rest-frame B band surface brightnesses may be higher by ~ 1 magnitude at that redshift (Lilly et al. 1998; Simard et al. 1999). The interpretation is hampered by selection effects (see Simard et al. 1999), and the implicit assumption that structural and surface brightness evolution of galaxies can be separated (see, e.g., Mao, Mo, & White 1998).

Vogt et al. (1996, 1997) provided an important additional constraint by measuring spatially resolved kinematics of disk galaxies out to $z \sim 1$, thus allowing comparisons of sizes and

luminosities of galaxies at fixed rotation velocity. Current data suggest that large, rapidly rotating disks exist at least out to $z \sim 1$, and that their luminosities are at most slightly brighter than equally massive disks today (Vogt et al. 1997).

In this *Letter*, we report on observations of a rapidly rotating, luminous galaxy at $z = 1.34$ dubbed L451. This galaxy shares many of its properties with the most massive spiral galaxies in the local Universe, and provides direct information on the properties of massive disks in the hitherto virtually unexplored redshift range 1 – 2. We use $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$.

2. OBSERVATIONS

Galaxy L451 ($\alpha = 8^h 48^m 40.0^s$, $\delta = +44^\circ 54' 13''$; J2000) is located in the vicinity of the cluster RDCS J0848+4453 at $z = 1.27$ (Stanford et al. 1997). This field has been studied extensively, both from the ground and with HST. Ground based *BRIJK_s* imaging data were previously reported in Stanford et al. (1997). Deep HST WFPC2 imaging data were described in van Dokkum et al. (2001a). Ten exposures were obtained in the I_{F814W} filter for a total of 27.8 ks. The galaxy falls just outside the region covered by a NICMOS H_{F160W} mosaic.

We included L451 in a multi-slit spectroscopic observation of RDCS J0848+4453. The galaxy has $K_s = 18.2$ (Stanford et al. 1997) and $z_{\text{phot}} = 1.40 \pm 0.08$ (see van Dokkum et al. 2001a), and was selected for deep spectroscopy because of the proximity of its photometric redshift to the redshift of the cluster. The

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field was observed on 2001 January 20–21 with the Low Resolution Imaging Spectrograph (Oke et al. 1995) on the Keck II Telescope, using multi-slit masks. The 6001mm^{-1} grating blazed at $1\mu\text{m}$ was used with $1''.2$ wide slits, giving a velocity resolution of $\sigma_{\text{instr}} \approx 80\text{ km s}^{-1}$ at 9000 \AA . Conditions were photometric, and the seeing was $\approx 0''.9$. Between exposures the spectra were moved along the slit to facilitate sky subtraction. The total integration time was 28.8 ks. The data reduction followed standard procedures for dithered multi-slit spectroscopic data (see, e.g., Stanford et al. 1997); details of the reduction are described in P. G. van Dokkum and S. A. Stanford, in preparation.

3. ANALYSIS

3.1. Redshift

The spectrum of L451 is shown in Fig. 1. The spectrum shows a prominent emission line at 8703 \AA and several absorption lines. The line is a doublet identified as $[\text{O II}] 3727\text{ \AA}$ at $z = 1.335$, and we conclude that L451 is a field galaxy unrelated to the foreground cluster at $z = 1.27$. The spectroscopic redshift is within 1σ of the photometric redshift.

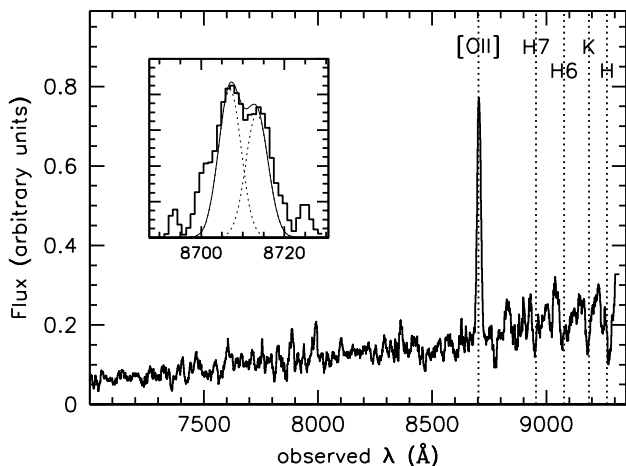


FIG. 1.— Integrated spectrum of L451, smoothed by a 13 \AA wide boxcar filter. The $[\text{O II}] 3727\text{ \AA}$ line redshifted to $z = 1.335$ can be identified, as well as higher order Balmer lines and the Ca II H, K lines. The inset shows the (unsmoothed) $[\text{O II}]$ doublet in the region of highest S/N ratio, which is $\sim 200\text{ km s}^{-1}$ removed from the systemic velocity.

3.2. Morphology and Spectral Energy Distribution

The HST I_{F814W} image of L451 is shown in Fig. 2. The galaxy is elongated, and has an irregular appearance. Several individual concentrations can be identified. Furthermore, the light is not concentrated towards the center but appears to be distributed in a ring. These features may indicate that the galaxy is not a relaxed system, and experienced a merger or interaction. However, since the observed I -band corresponds to the rest-frame U -band for a galaxy at $z = 1.34$, the irregular morphology can also be due to patchy star formation.

In Fig. 3 the morphology in the I band is compared to that in the K -band. For an object at $z = 1.34$ the K band corresponds to the z -band in the rest-frame, which is much less sensitive to on-going star formation than the U -band. The resolution of the K -band image is slightly enhanced (from $1''.3$ to $0''.9$ FWHM) by

a CLEAN reconstruction (Högbom 1974) using a nearby bright star. The I -band image is created by smoothing the WFPC2 image to $0''.9$ resolution and resampling. The galaxy is compact in K , and its center coincides with the center of the ring seen in the I -band. The K -band morphology argues against the merger hypothesis, and we conclude that the irregular appearance of L451 in the rest-frame near-UV is probably caused by star formation in an otherwise regular galaxy.

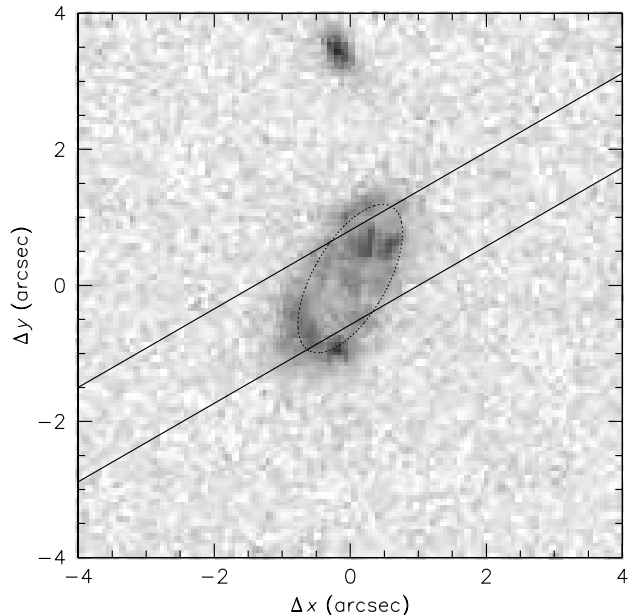


FIG. 2.— HST WFPC2 image of L451 in the I_{F814W} filter. The solid lines show the slit that was used in the Keck observations. The ellipse indicates the adopted inclination and position angle of L451. The galaxy has an irregular morphology in the rest-frame U band.

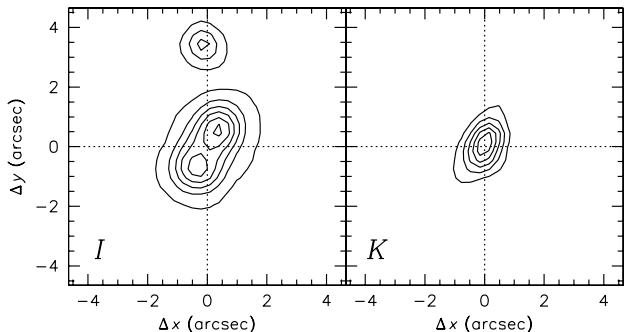


FIG. 3.— Comparison of morphology in I_{F814W} and K filters (rest-frame U and z). The I_{F814W} image was smoothed and resampled to match the K band resolution. Note the regular, compact morphology of the K band image in comparison to the smoothed I band image.

This interpretation is supported by the integrated spectral energy distribution (SED) of L451, shown in Fig. 4. The galaxy is quite red: $I - K = 3.8$ in a $3''$ aperture, implying that the K -band morphology represents the distribution of the bulk of the stellar mass. Remarkably, the SED is very well fitted by that of *present-day* Sb/c galaxies as obtained from Coleman, Wu, & Weedman (1980). We conclude that L451 is probably not a merger, but a very luminous early-type spiral galaxy. We use the observed J magnitude and $J - K$ color to obtain the rest-frame V magnitude (see van Dokkum et al. 1998). Using

$J = 20.4$ and $J - K_s = 2.25$ we obtain $M_V = -22.3 \pm 0.2$, or $\sim 3L_*$.

Early-type spiral galaxies in the local Universe often show a similar wavelength dependence of morphology. The near-UV light traces star forming regions which may be distributed in a disk or a ring, whereas the near-IR light is usually dominated by the bulge (e.g., Kuchinski et al. 2000).

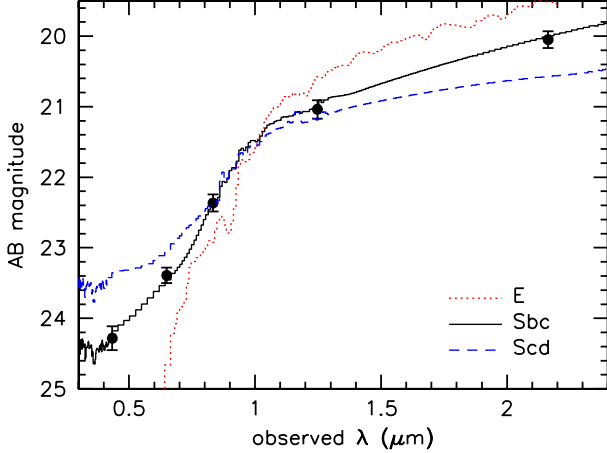


FIG. 4.— Spectral energy distribution of L451. Overplotted are the SEDs of various galaxy types in the nearby Universe (Coleman, Wu, & Weedman 1980), redshifted to $z = 1.335$. The observed SED is much redder than that of star forming late-type galaxies, and is very well fitted by that of present-day Sb/c galaxies.

3.3. Inclination

The resolution and depth of our ground based data are not sufficient to determine the size and inclination of the disk. Therefore, we determine these parameters from the I_{F814W} image, with the caveat that the light is dominated by star forming regions. The position angle and inclination of the galaxy are obtained from an ellipse fit to the star forming ring (indicated in Fig. 2). We find $PA = 150 \pm 7$ degrees and $(b/a) = 0.44 \pm 0.05$. Assuming that L451 has an intrinsically circular disk whose thickness is less than $\sim 20\%$ of its diameter, we infer that L451 is inclined by 65 ± 5 degrees. The diameter of the ring is $\approx 2''.7$, corresponding to $\approx 19 h_{75}^{-1}$ kpc. High resolution images in the rest-frame optical are needed to determine the exponential scale length of the disk. Such data may also be used to determine whether the galaxy has a bar, as suggested by its ring-like morphology in the rest-frame near-UV (e.g., Kormendy 1979).

3.4. Rotation Velocity and Tully-Fisher Relation

The position of the slit that was used in the LRIS observations is indicated in Fig. 2. The major axis of the galaxy and the slit are misaligned by only $\sim 30^\circ$. As is evident in Fig. 5 the [O II] line displays a significant velocity gradient. Radial velocities at each position along the slit are obtained by fitting a double Gaussian profile. The line ratio $r_{\text{O II}} \equiv F(\lambda 3729)/F(\lambda 3726)$ is determined from the observed profile of the doublet at the position with the highest signal-to-noise ratio (see Fig. 1), and assumed to be constant over the extent of the galaxy. The observed line ratio $r_{\text{O II}} \sim 0.8$ implies an electron density $N_e \sim 10^3 \text{ cm}^{-3}$ (Odell & Castaneda 1984). Such a high density is unusual for extragalactic H II regions (e.g., Shields 1990); we note that L451 is not detected in a 185 ks Chandra X-ray observation (Stanford et al. 2001).

The resulting velocity curve is shown in the lower panel of Fig. 5. Horizontal bars show the rows that were averaged in the 2D spectrum, and the positions are intensity weighted averages. The open circle shows the velocity derived from the Ca II H and K lines. The data points are highly correlated because of the seeing, and the shape of the rotation curve is not constrained by our data. The total velocity range is 510 km s^{-1} , and the implied maximum observed rotation velocity is $255 \pm 15 \text{ km s}^{-1}$.

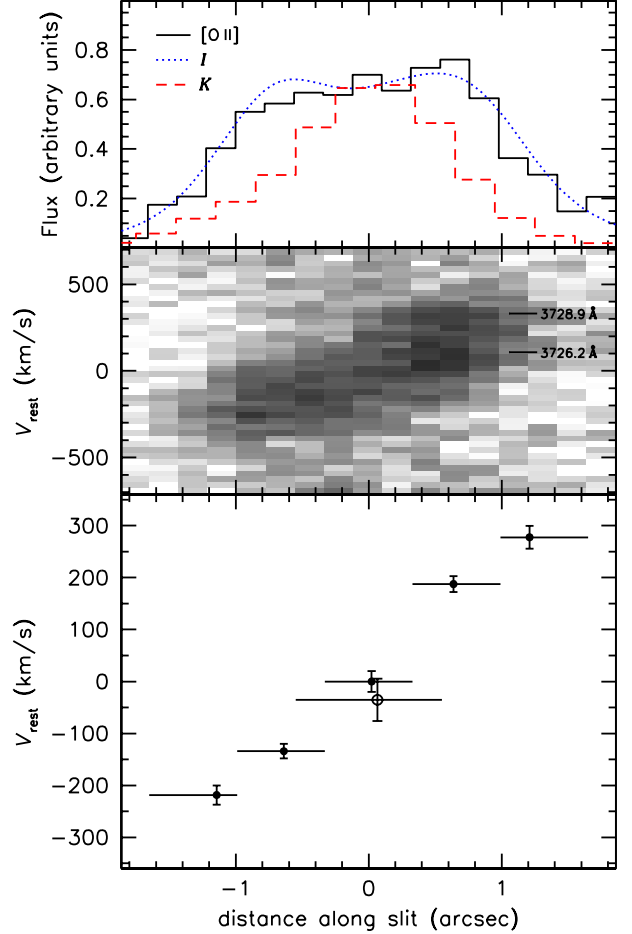


FIG. 5.— Radial velocity along the slit derived from the [O II] 3727 Å line (lower panel). The middle panel shows the 2D spectrum, and the top panel shows the scaled distributions of the [O II] line, the I -band light, and the K -band light along the slit. The observed velocity range $2V_{\text{max}} \approx 510 \text{ km s}^{-1}$. The open circle shows the velocity derived from the Ca II H and K lines.

The observed velocities are a convolution of the underlying velocity field, the distribution of the line emitting gas, the inclination of the galaxy, and the position of the slit. Vogt et al. (1996, 1997) used exponential disk models to interpret their observed rotation curves. Such models are not appropriate for L451: the top panel of Fig. 5 shows that the [O II] emission follows the distribution of the near-UV continuum light, which is dominated by a few individual star forming regions (see Fig. 2). As a result, modelling of the underlying velocity field is highly degenerate. Applying a straightforward inclination correction gives a conservative estimate of the maximum rotation velocity $V_{\text{max}} = 290 \pm 20 \text{ km s}^{-1}$. This is strictly a lower limit, since there is no indication that our observations sample the flat part of the rotation curve.

Following Vogt et al. (1996, 1997) we determine the offset of L451 from the present-day Tully-Fisher relation (Tully & Fisher 1977). The Tully-Fisher relation predicts $M_B^a = -21.4 \pm 0.2$ for $V_{\max} = 290 \text{ km s}^{-1}$ (e.g., Pierce & Tully 1992, Verheijen 2001). The uncertainty reflects the differences in slope and offset of the relation obtained from different local samples. Applying the extinction correction of Tully & Fouque (1985) gives $M_V^a = -22.8 \pm 0.3$ for L451. Taking $B - V = 0.7$ for present-day massive spiral galaxies (de Jong 1995) we conclude that L451 is overluminous by 0.7 ± 0.4 magnitudes. Because V_{\max} may be underestimated, this offset is strictly an upper limit.

Although it is hazardous to draw conclusions from a single object, our results for L451 are consistent with studies by Vogt et al. (1996, 1997) of field galaxies at lower redshift. They are also consistent with models of Ferreras & Silk (2001), which predict 0 – 1 magnitudes of luminosity brightening at $z = 1.3$. We note that these models do not treat the evolution of the bulge and the disk separately; if bulges evolve in the same way as elliptical galaxies, the bulge of L451 is expected to be 1 – 1.5 magnitudes brighter than low redshift bulges of the same mass (van Dokkum et al. 1998, 2001b).

4. DISCUSSION

Provided that L451 is not exceptional, it may prove challenging to produce such regular, massive bulge-disk systems as early as $z \approx 1.3$ in current hierarchical galaxy formation models. It is generally thought that the properties of disks are closely tied to those of the dark halos in which they formed (e.g., Fall & Efstathiou 1980), and in hierarchical clustering models present-day large disks were formed late, at $z \lesssim 1$ (e.g., Mo et al. 1998, van den Bosch 1998). High redshift galaxies with large rotation velocities do exist in these models, but they are small. For a galaxy at $z = 1.3$ with $V_{\max} = 290 \text{ km s}^{-1}$ the predicted scale length $R_d \sim 3 \text{ kpc}$ (Mao et al. 1998) — approximately one third the size of the star forming ring of L451. High resolution images in the rest-frame optical or near-IR are necessary to measure the exponential scale length of L451, for a direct comparison to low redshift samples.

The local space density of $L \geq 3L_*$ galaxies is only $\sim 7 \times 10^{-5} h_7^3 \text{ Mpc}^{-3}$ (Blanton et al. 2001), and surveys over large volumes are required to determine the space density of objects such as L451. As an example, the expected number of $L \geq 3L_*$

galaxies between $z = 1.3$ and $z = 1.4$ in the K -selected Cowie et al. (1996) sample is only ~ 0.3 (assuming no luminosity evolution); hence their absence in this survey is not very constraining. Combining large area K -band surveys (e.g., Daddi et al. 2000) with accurate photometric redshifts may be the most efficient way to select candidate massive disk galaxies at $1 < z < 1.5$.

In hierarchical models, virtually all present-day $L \gtrsim 2.5L_*$ galaxies have Ly-break progenitor galaxies (Baugh et al. 1998), and it is interesting to compare the properties of L451 to those of known galaxies at $z \approx 3$. Ly-break galaxies are compact (Gialalisco, Steidel, & Macchetto 1996), and recent [O III] 5007 Å spectroscopy shows that they have modest line widths, of $50 - 110 \text{ km s}^{-1}$ (Pettini et al. 2001). Taking these results at face value, several mergers are required to build up a galaxy of the size and mass of L451. After these mergers the remaining gas in the halo has to settle into a disk. These processes need to be efficient, and be completed in $\sim 2 \times 10^9 \text{ yr}$.

Alternatively, large, evolved galaxies such as L451 may yet have escaped detection at higher redshift. The galaxy is quite faint in the rest-frame ultra-violet (see Fig. 4), and if it were placed at $z = 3$ it would have $I_{AB} \approx 26.5$, more than 1 magnitude fainter than typical Ly-break galaxies. Furthermore, in the region between the star forming regions its surface brightness would be $I_{AB} \gtrsim 29 \text{ arcsec}^{-2}$, undetectable even in the Hubble Deep Fields. The star forming regions would show as distinct objects $\sim 2''$ and $\sim 400 \text{ km s}^{-1}$ apart, making it very difficult to assess the true nature of the galaxy. If disk galaxies do not evolve strongly in luminosity, as suggested by the Tully-Fisher results to $z \approx 1.3$, very deep IR imaging may be the only way to detect large, massive disks at $z \sim 3$.

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